# Beam Dump eXperiments with electron beams

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**Beam dump experiments at the intensity frontier are a powerful tool to explore the Dark Sector. We present two proposals that will make use of the high-intensity electron beams of Jefferson Lab (up to 11 GeV) and MESA at Mainz (155 MeV) to produce and detect Light Dark Matter in the MeV to GeV mass region. The two experiments share a common detector concept: an electromagnetic calorimeter surrounded by an active veto, optimized to their respective mass and energy ranges. An alternative option, using a low-pressure, negative-ion TPC is also proposed. With a year of beam, BDX and DarkMesa will explore unexplored regions of the parameter space of dark-matter coupling versus mass, exceeding the discovery potential of existing and planned experiments by up to two orders of magnitude. Both experiments were approved by the Program Advisory Committees of their respective labs and are waiting to move into the construction phase.**

## Introduction

If the dark and visible matter have sufficiently large interactions to achieve thermal equilibrium during the early universe, the resulting DM abundance greatly exceeds the observed density in the universe today; thus, a thermal origin requires a sufficient DM annihilation rate to deplete this excess abundance and agree with observation at later times. For thermal dark matter below the GeV scale, this requirement can only be satisfied if the dark sector contains comparably light new force carriers to mediate the necessary annihilation process. Presently there are significant regions of parameter space that are uncovered by existing experiments. We present a program of beam dump experiments that are sensitive to such new light-force carriers. See Ref. (1) for details.

Such "mediators" must couple to visible matter and be neutral under the Standard Model (SM) gauge group, so the options for possible mediators can be enumerated in an economical list. A popular representative model involves a so-called "dark photon" $A'$ with mass $m_{A'}$ and Lagrangian in the interaction basis(2)

$$\mathcal{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\epsilon}{2}F'_{\mu\nu}F_{\mu\nu} + \frac{m^2_{A'}}{2}A'_\mu A'^\mu + g_D A'_\mu J^\mu_D$$

where $F'_{\mu\nu} \equiv \partial_\mu A'_\nu - \partial_\nu A'_\mu$ is the dark photon field strength, $F_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu$ is the electromagnetic field strength, $g_D \equiv \sqrt{4\pi\alpha_D}$ is the dark gauge coupling, $J^\mu_D$ is the current of DM fields, and $\epsilon$ parametrizes the degree of kinetic mixing between dark and visible photons. Although the interaction basis Lagrangian initially has no coupling between the $A'$ and SM particles, diagonalizing the kinetic term induces an $\epsilon$ proportional coupling between $A'$ and the EM current of SM particles $f$ with charges $Q_f$. The phenomenology of the DM interaction depends on the DM/mediator mass hierarchy and on the details of the dark current $J^\mu_D$. If there is only one dark sector state, the dark current generically contains elastic interactions with the dark photon. However, if there are two (or more) dark sector states the dark photon can couple to the dark sector states off-diagonally. This latter scenario can lead to distinct signatures, for which beam-dump experiments are especially suited.

In the paradigm of a thermal origin for DM, it would have acquired its current abundance through direct or indirect annihilation into SM. If the mediator is heavier than the DM, the thermal relic abundance is achieved via direct annihilation $\chi\bar{\chi} \to ff$, where $f$ are SM fermions, with a corresponding annihilation rate scaling as $\sigma v_{\chi\chi\to\bar{f}f} \propto y \equiv \epsilon^2\alpha_D\left(\frac{m_\chi}{m_{\rm MED}}\right)^4$. This scenario offers a predictive target for discovery or falsifiability, since there is a *minimum* SM-mediator coupling compatible with a thermal history that experiments can probe.

**The BDX experiment at JLab** The fixed target phenomenology of stable LDM particles is well-described by the simple case presented in the previous section (for further details see Ref. (1)). In an electron beam-dump experiment, LDM par-

# Beam Dump eXperiment with electron beams

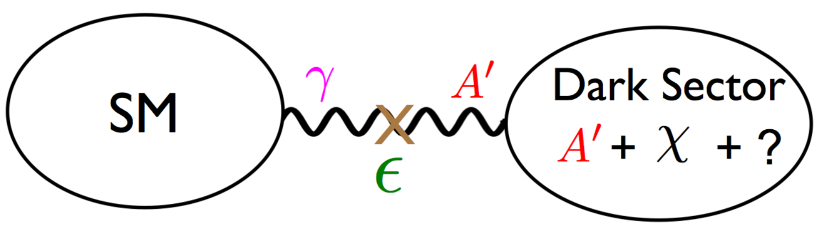
***M.Battaglieri***
***JLab/INFN***
***(on behalf of BDX Collaboration)***

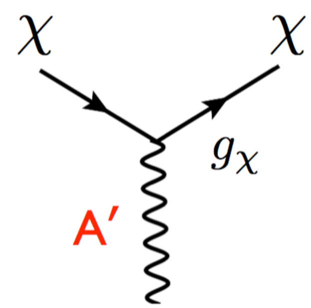
Outline

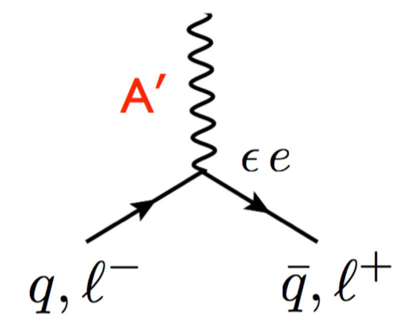
- Physics motivations
- Work plan & paper
- Snowmass  expected outcome

# Dark forces and dark matter

## (Light WIMPs - light mediators)



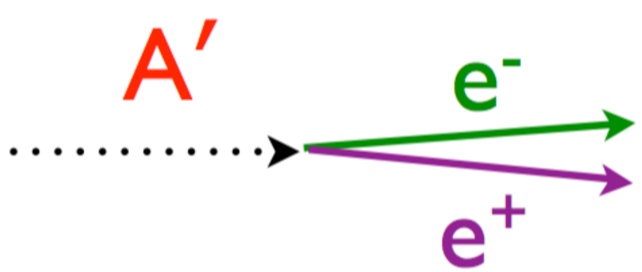



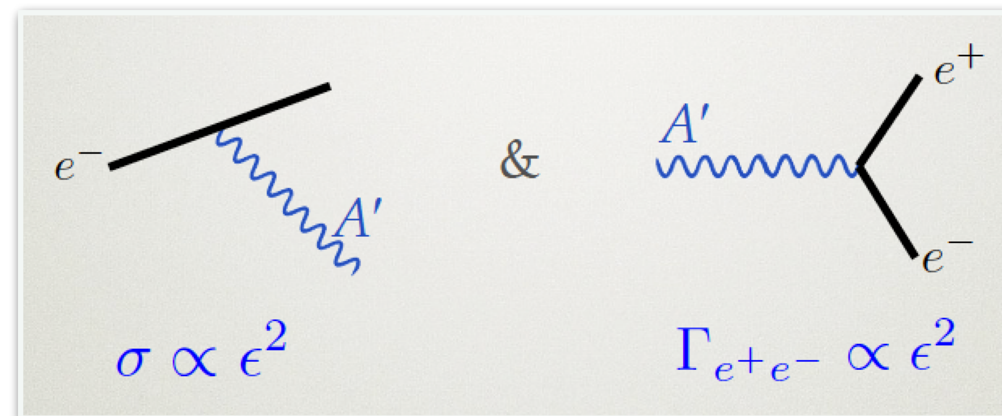

4 parameters: $m_\chi, m_{A'}, \epsilon, g_\chi$

$$m_\chi \sim m_{A'} \sim \mathrm{MeV} - 5\ \mathrm{GeV}$$

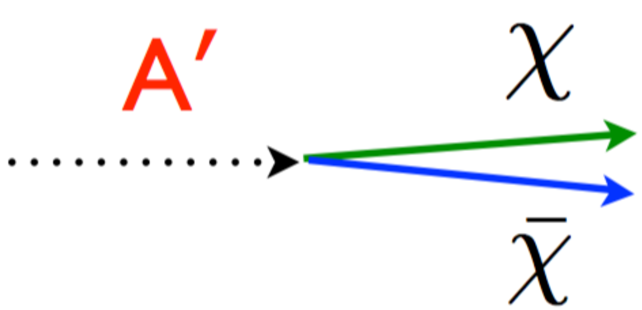
**Visible**



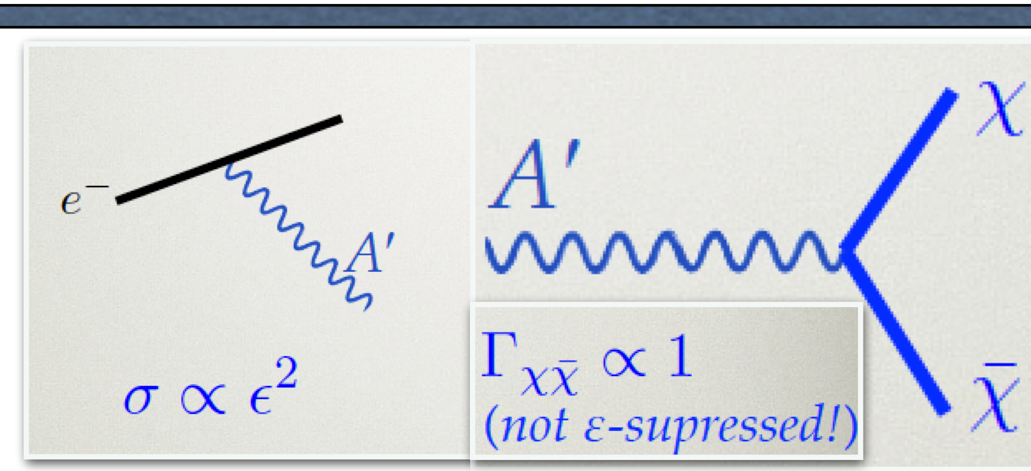

- *Minimal* decay
- Decay regulated by $\varepsilon^2$
- Independent of $m_\chi$
- Requires $m_{A'} < 2m_\chi$




**Invisible**




- Depends on 4 parameters
- $m_{A'} > 2m_\chi$ (on-shell)
- $\alpha_D = g^2_\chi/4\pi >> \varepsilon^2\alpha_{EM}$

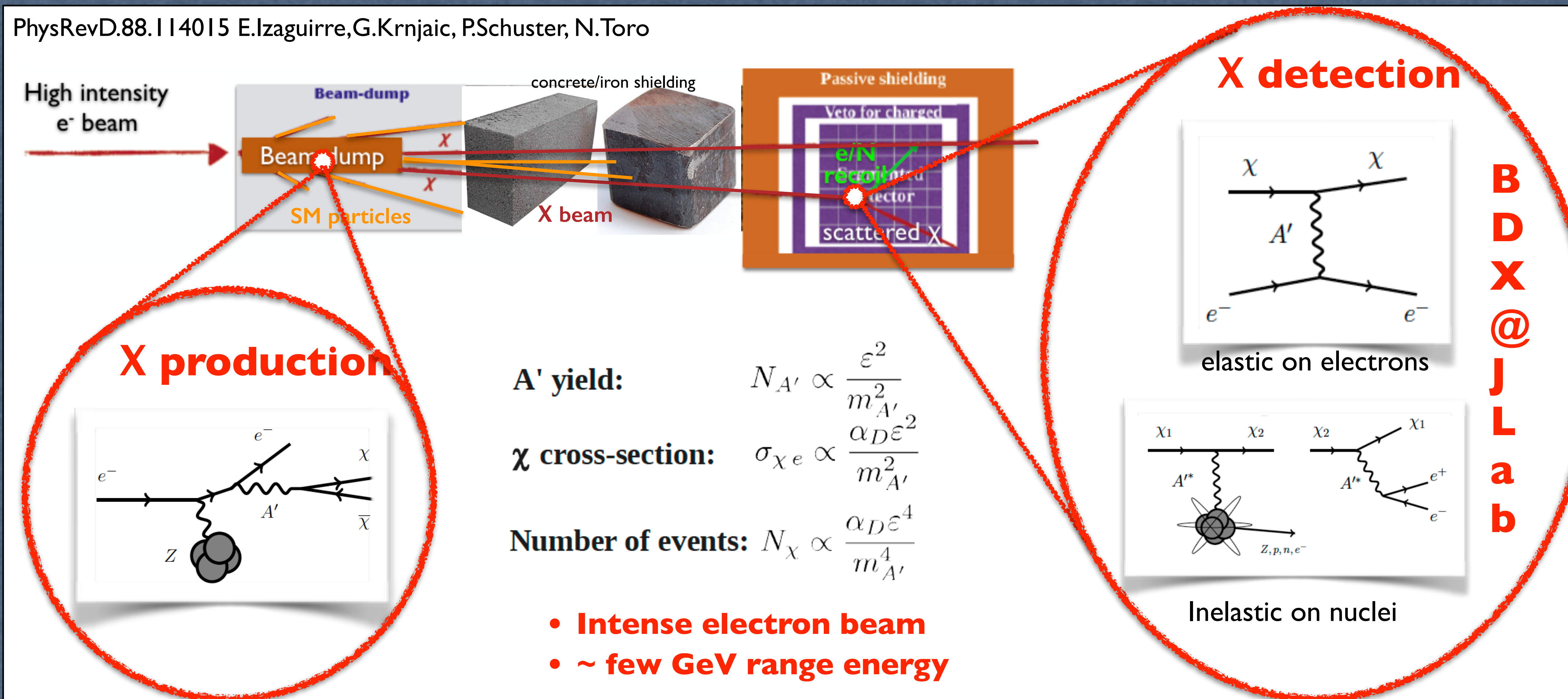


# The BDX experiment

Two step process

I) An electron radiates an A' and the A' promptly decays to a χ (DM) pair

II) The χ (in-)elastically scatters on a $e^-$/nucleon in the detector producing a visible recoil (GeV)



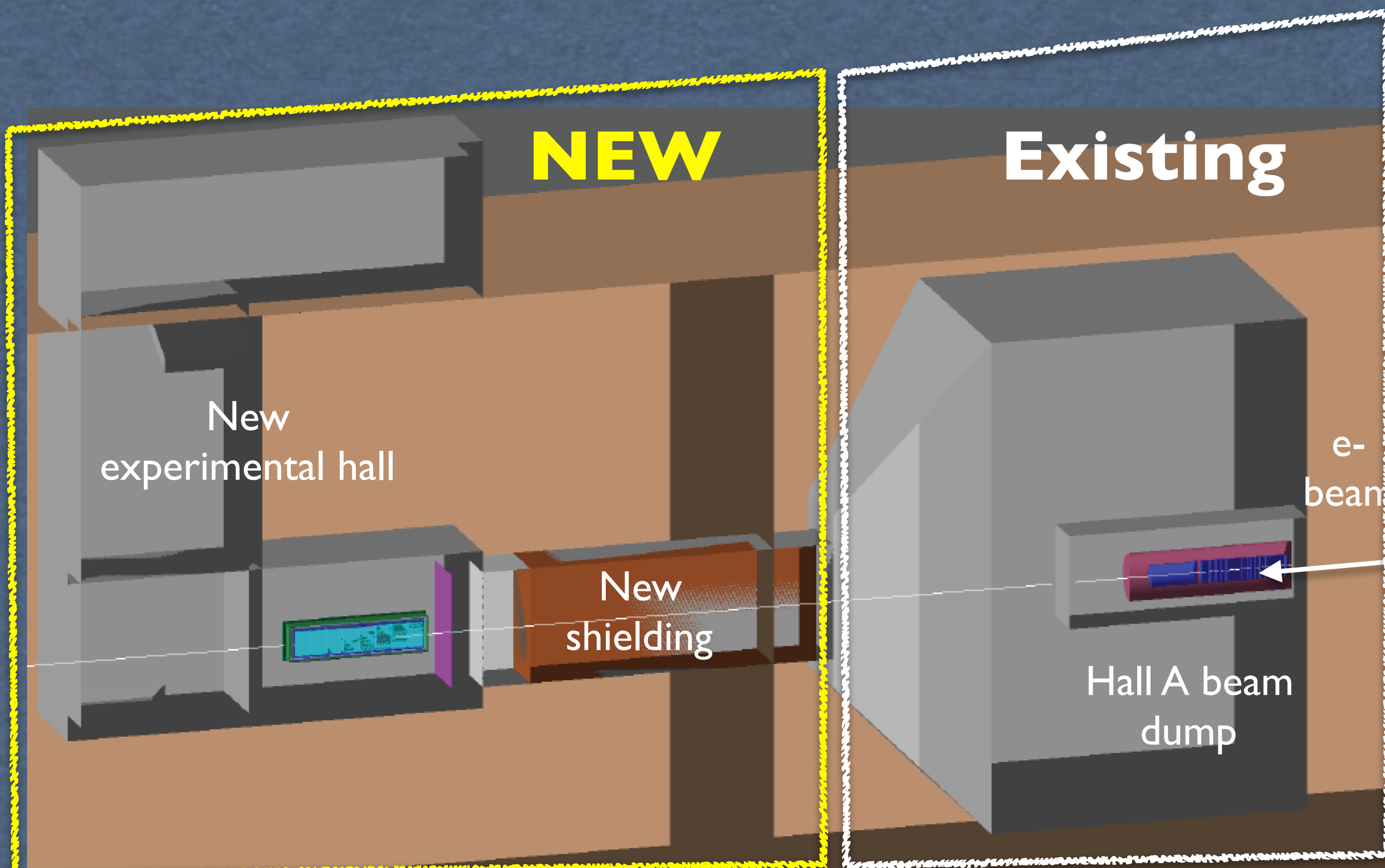

**Experimental signature in the detector:**

**X-electron → EM shower ~GeV energy**

# BDX at JLab

★ High energy beam available: 11 GeV
★ The highest available electron beam current: ~65 uA
★ The highest integrated charge: $10^{22}$ EOT (41 weeks)

★ BDX detector located downstream of Hall-A beam dump
★ New underground experimental hall



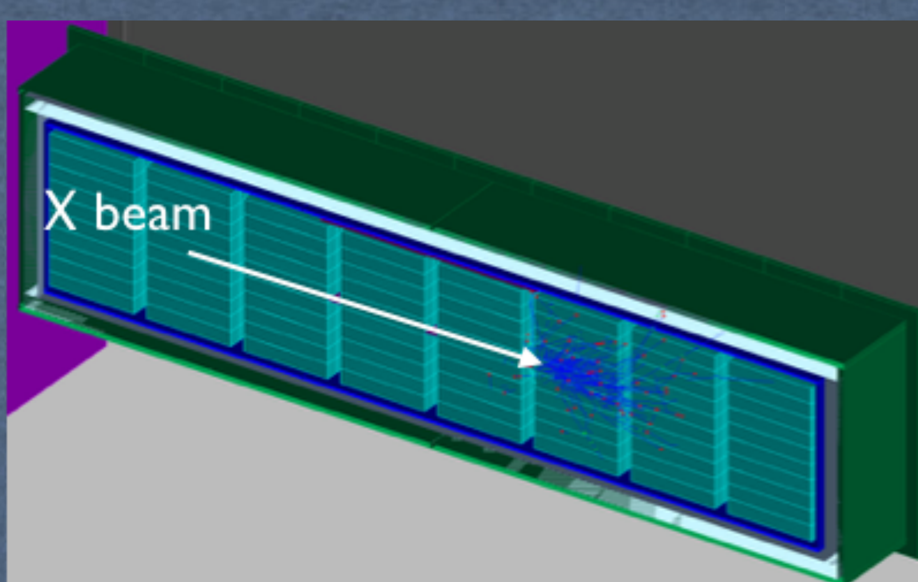

# The BDX detector

## Detecting the X

## E.M. Calorimeter

A **homogeneous crystal-** based detector combines all necessary requirements

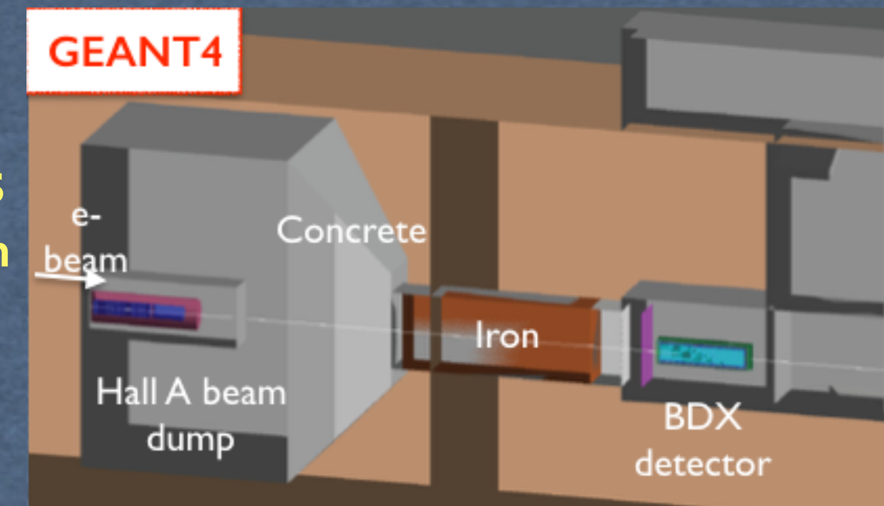
**Modular EM calorimeter**
- 8 modules 10x10 crystals each
- 800 CsI(Tl) crystals (from BaBar EMCal)
- 6x6 mm$^2$ Hamamatsu SiPM readout
- 50 x 55 x 295 cm$^3$

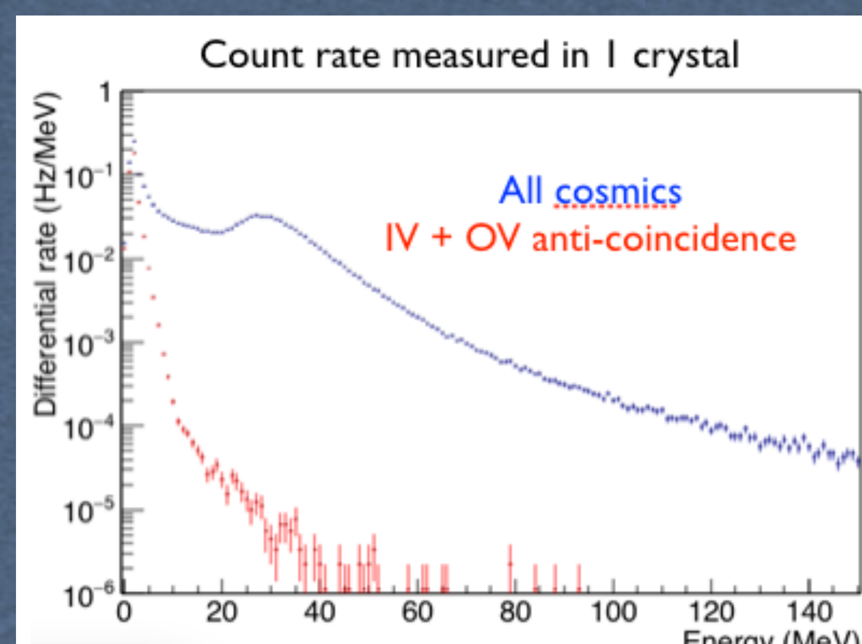

## Rejecting the bg

### Two active veto layers

**Plastic scintillator +WLS with SiPM and PMT readout**
- Outer Veto: 2cm thick
- Inner Veto: 1 cm thick
- Lead Vault: 5cm thick




★ Cosmic background measured with the BDX detector prototype in CT

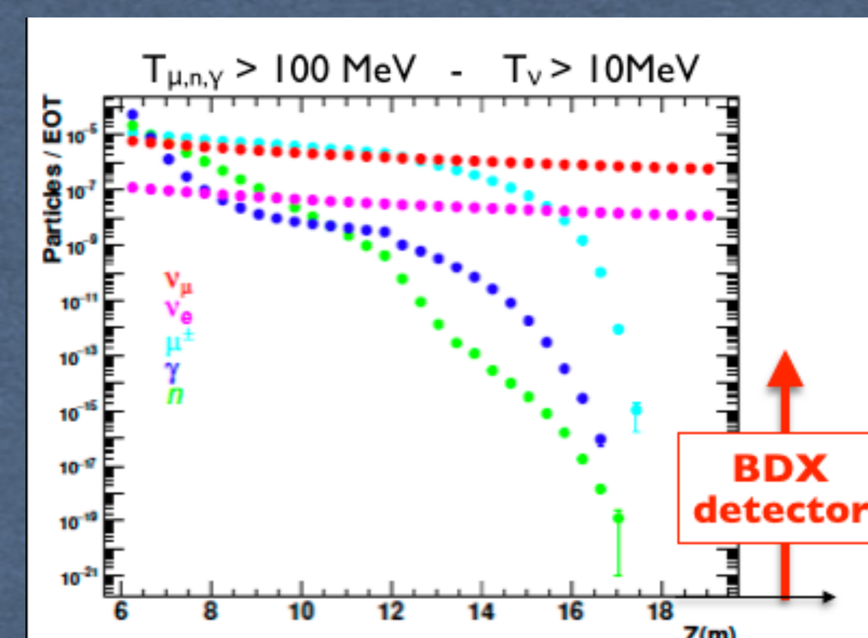



**Expected cosmic bg counts in BDX lifetime < 2 counts**

★ Bem-on bg by GEANT4, $E>E_{Thr}$

★ Muons are ranged out by the iron shielding

★ Non-negligible contribution of high energy ne detector by CC: $\nu + N \rightarrow X + e^-$




**Expected beam-related counts in BDX lifetime ~ 10 counts**

# BDX expected reach

## Beam time request

- $10^{22}$ EOT (65 uA for 285 days)
- BDX can run parasitically to any Hall-A $E_{beam}$>10 GeV experiments (e.g. Moeller)

**Beam-related background**

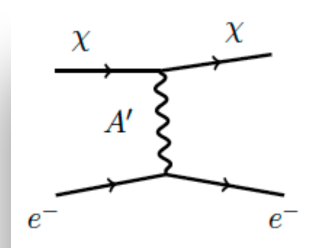
| Energy threshold | $N_\nu$ (285 days) |
|---|---|
| 300 MeV | ~10 counts |

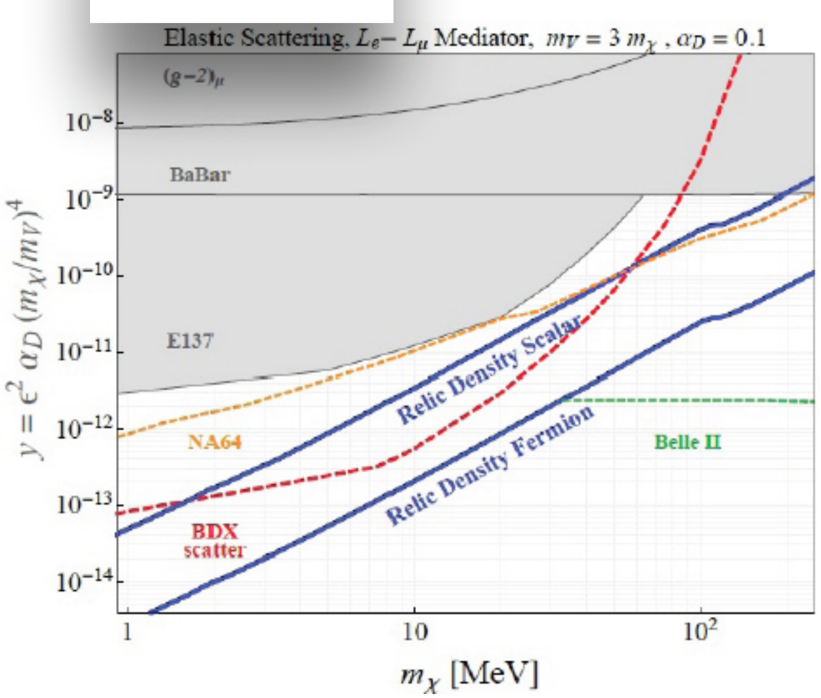
**Cosmic background**

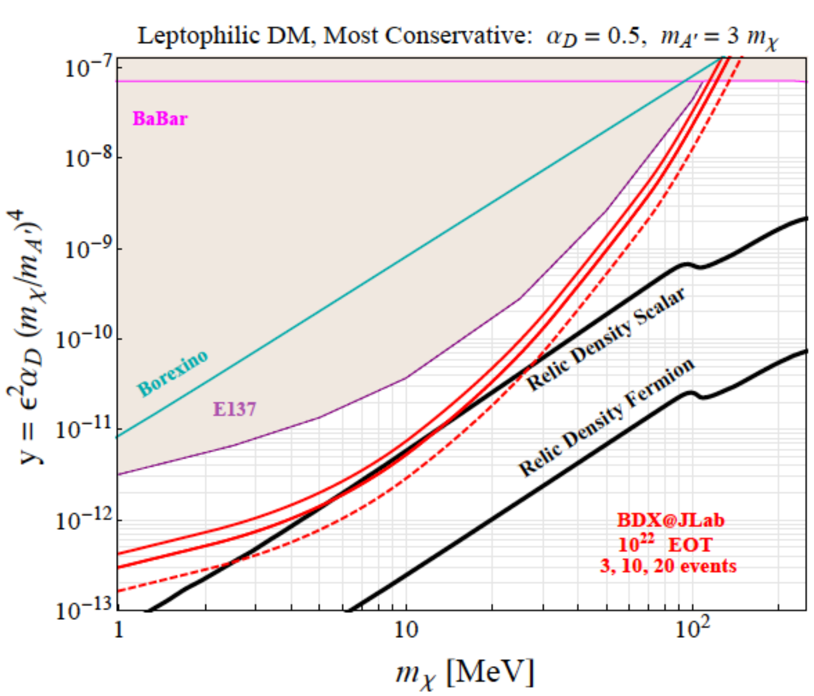
| Energy threshold | $\sqrt{Bg}$ (285 days) |
|---|---|
| 300 MeV | <2 counts |

**BDX sensitivity is 10-100 times better than existing limits on LDM**

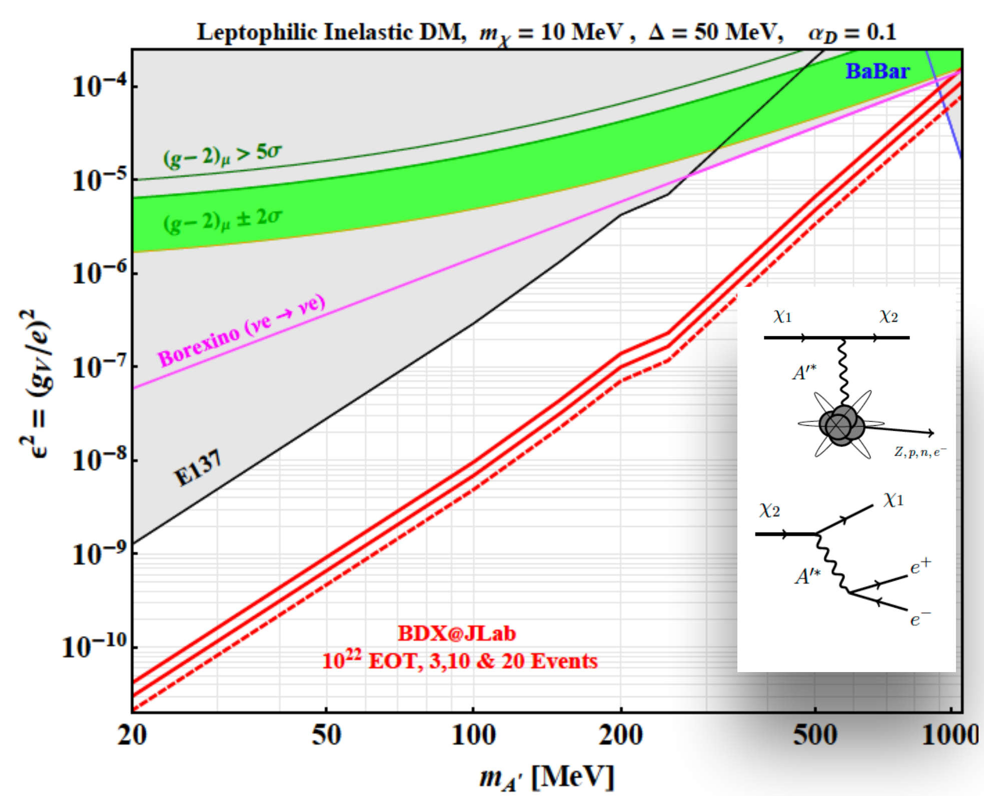
### Elastic X-e⁻ scattering - BDX reach



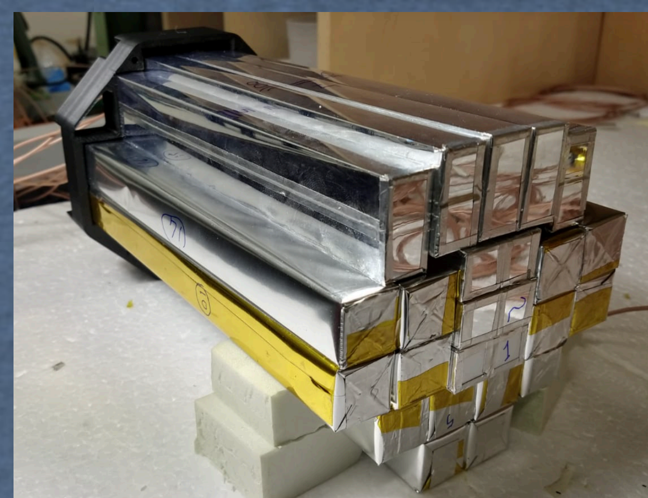

### Inelastic X-N scattering

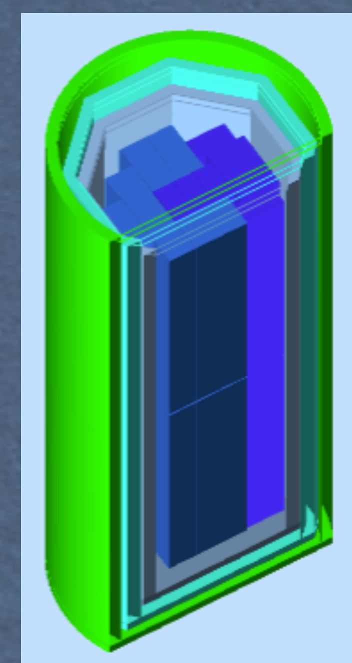


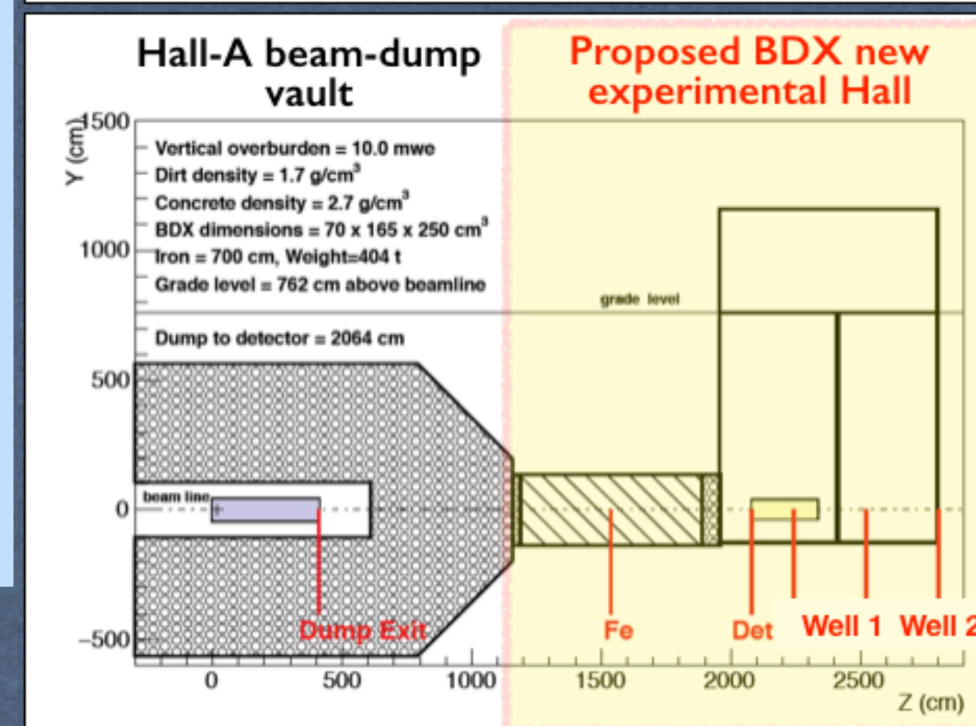
# BDX-MINI

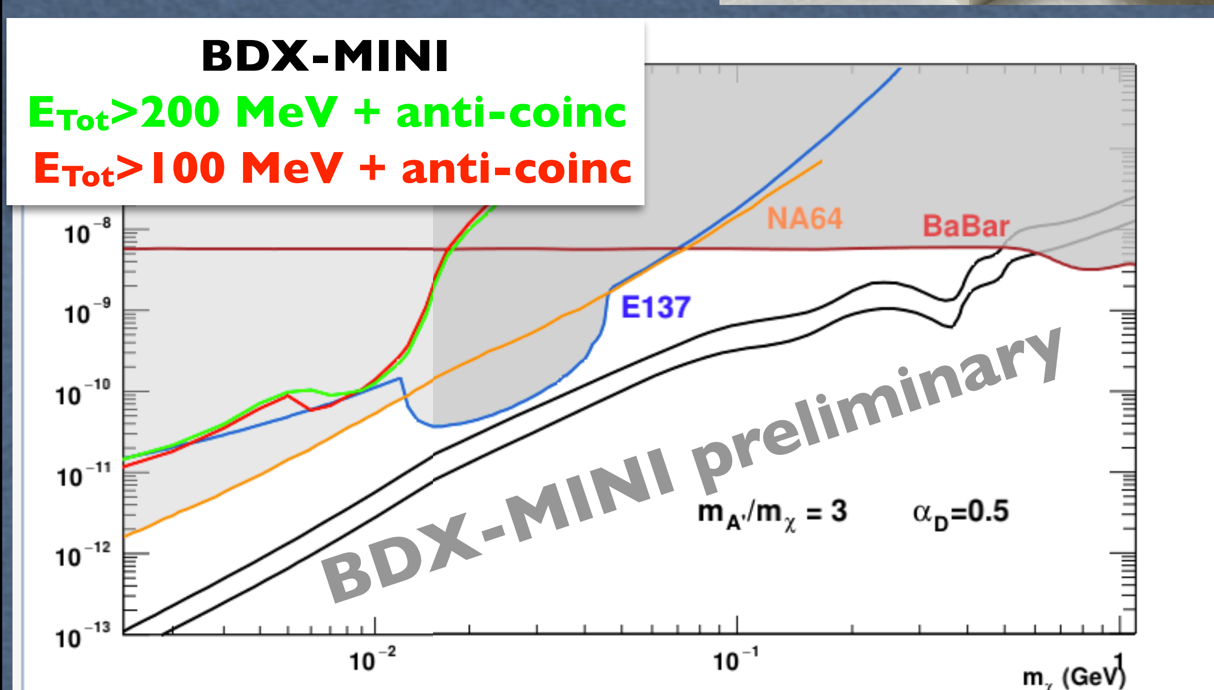
- Two wells dug for bg muon tests
- $E_{beam}$=2.2 GeV, no muons
- Limited reach but first physics result!


- 44 PbWO4 PANDA/FT-Cal crystals (~1% V BDX)
- 6x6 mm2 SiPM readout
- 2 active plastic scintillator vetos: cylindrical and octagonal (8 sipm each) + 2x lids + Passive W shielding



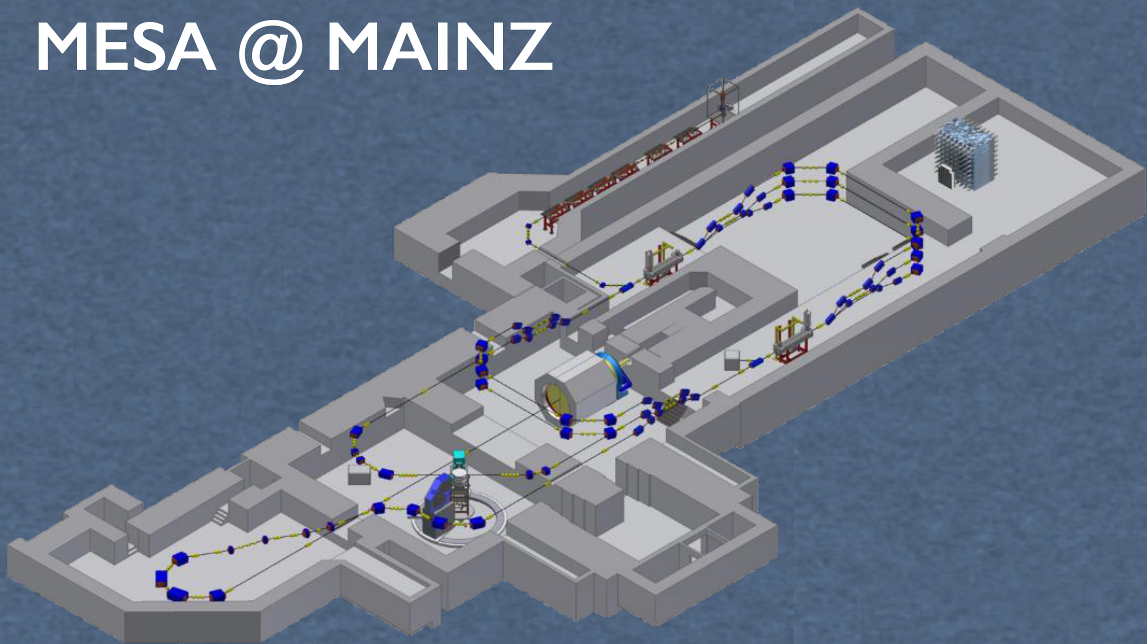




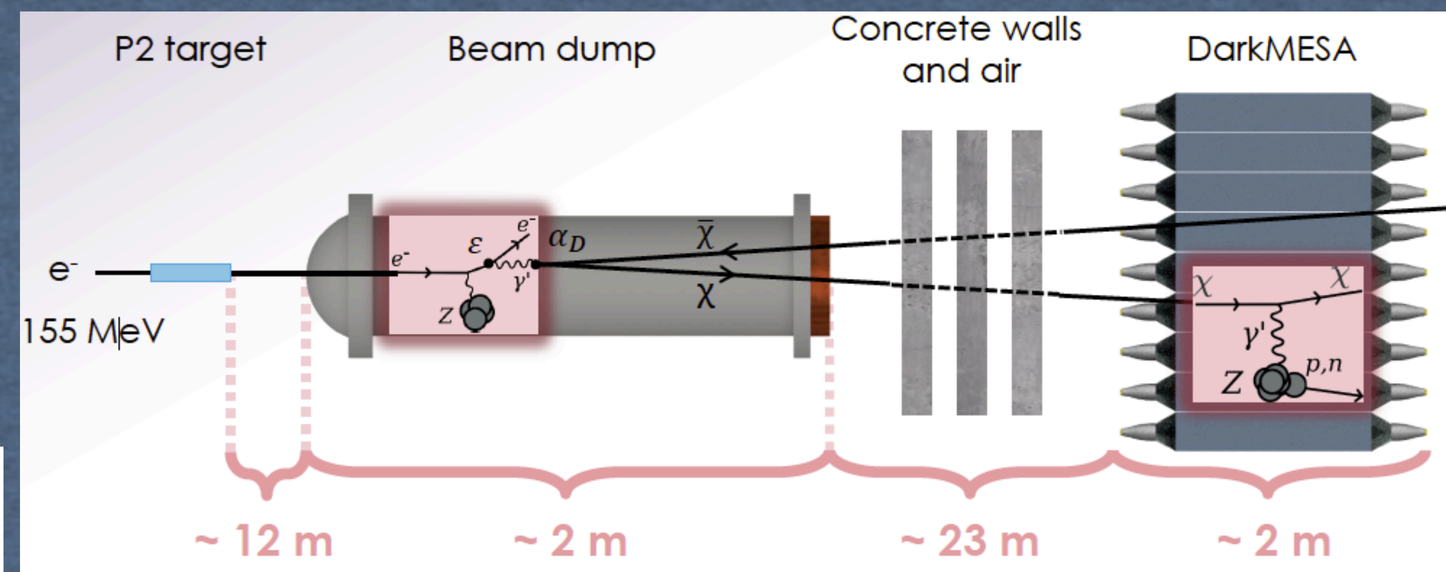



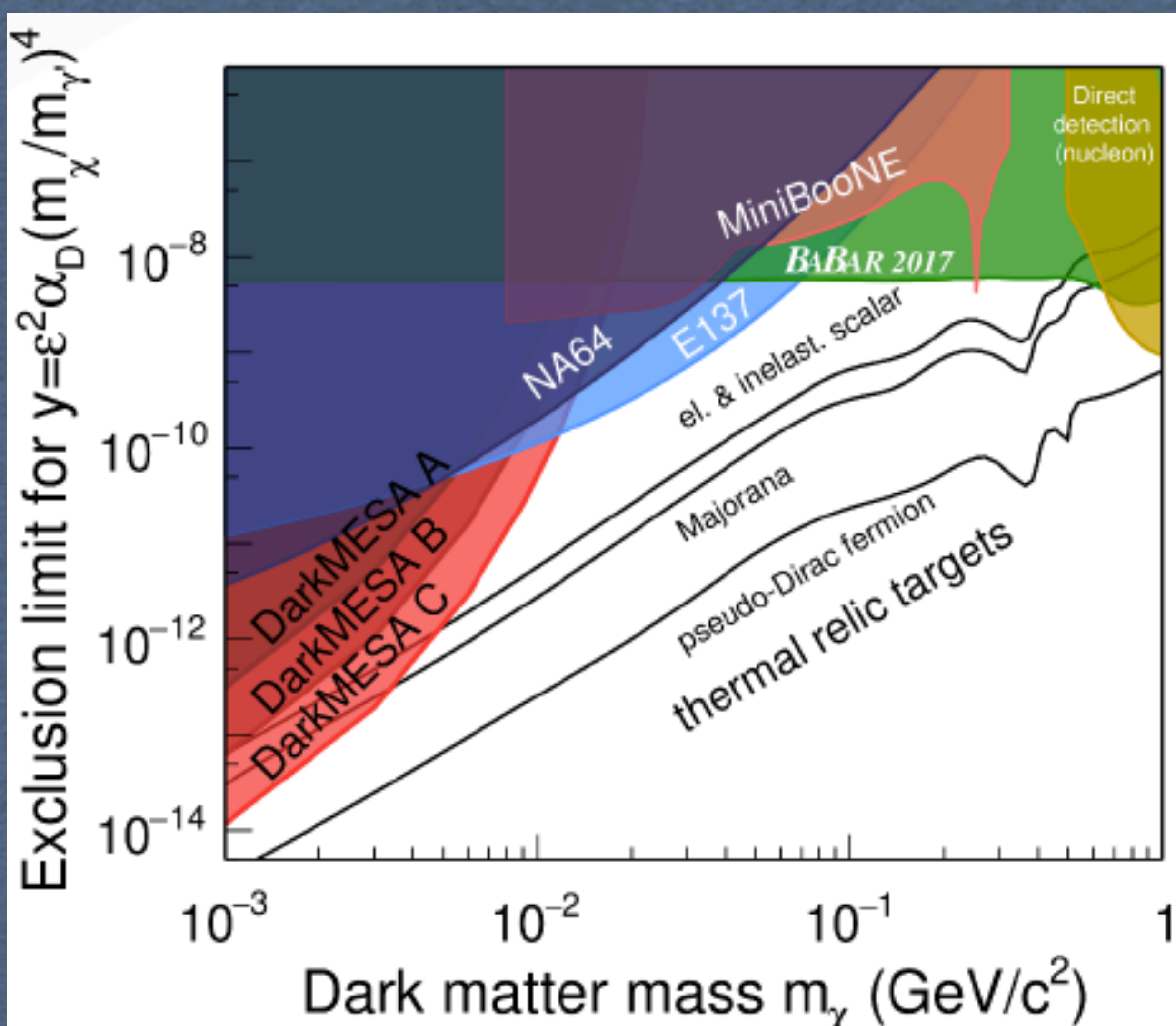

- Installed in March 2019
- Run form Dec 2019 to Aug 2020
- Collected 4e21 EOT (40% BDX!) in ~4 months (+ cosmics)
- Good detector performance with high duty factor
- Data analysis in progress

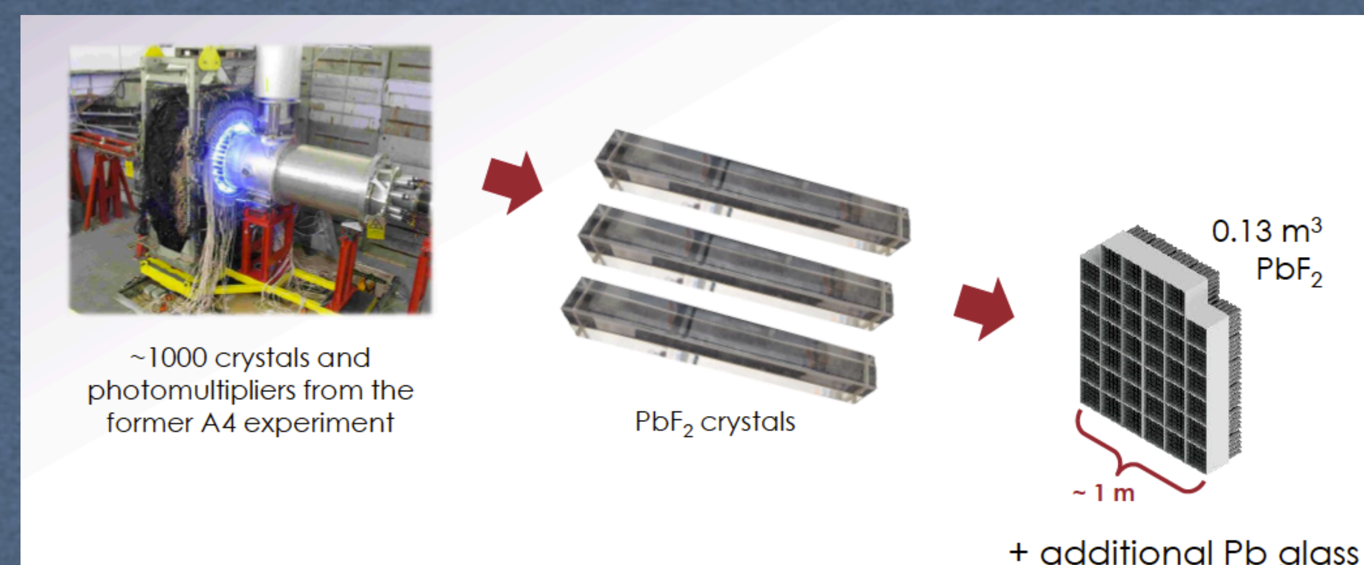
## MESA @ MAINZ



# BeamDump@MAINZ
# DARKMESA




- $\alpha D$=0.5and $m\gamma'=3 \cdot m\chi$
- $3 \cdot 10^{22}$ EOT
- Energy detection threshold 14 MeV
- Detector efficiency 90%
- No backgrounds

| Workplan | Completion |
|---|---|
| Theory and physics case | 100% |
| Detector R&D: signal detection and BG rejection | 100% |
| Detector prototyping: cosmic BG assessment | 100% |
| Detector prototyping: beam-related BG assessment | 100% |
| BDX proposal submission to JLab Program Advisory Comm | Full approval: Rate A |
| Costs estimate | baseline defined (FOA presented) |
| BDX-MINI run | 100% |
| Infrastructure | waiting |
| Running BDX | 2027-2028 in parallel Moeller exp |

- BDX is ready for the construction phase (waiting for the new Hall to be built)
- Ready for a contributed paper
- Between now and Snowmass: publish BDX-MINI results
- Expected Snowmass outcome:
  recommendation: funding infrastructures (new hall + shielding) to run BDX at JLab